Effects of the $\Lambda(1405)$ on the Structure of Multi-Antikaonic Nuclei

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Abstract

The effects of the $\Lambda(1405)$ (Λ^*) on the structure of the multi-antikaonic nucleus (MKN), in which several K^- mesons are embedded to form deeply bound states, are considered based on chiral symmetry combined with a relativistic mean-field theory. It is shown that additional attraction resulting from the Λ^* pole has a sizable contribution to not only the density profiles for the nucleons and K^- mesons but also the ground state energy of the K^- mesons and binding energy of the MKN as the number of the embedded K^- mesons increases.

Key words: multi-antikaonic nuclei, chiral symmetry, kaon condensation, subthreshold resonance $\Lambda(1405)$
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1. Introduction

Exploring multi-strangeness systems is an important aspect of understanding hadron dynamics in dense matter. Kaon condensation in neutron stars may exist as a strangeness-nonconserving system, where kaon condensates are spontaneously produced from normal matter through weak processes, $N + n \to N + p + K^-$, $N + e^- \to N + K^- + \nu_e$ ($N = p, n$)[1]. Recently multi-antikaonic nuclei (abbreviated as MKN), where several antikaons (K^- mesons) are bound in the ground state of the nucleus, have been investigated[2, 3], stimulated by the proposal to explore deeply bound kaonic nuclear states and subsequent theoretical and experimental studies[4]. The MKN is a strangeness-conserving system and should be formed by embedding a K^- meson in the nucleus through strong processes. Both the kaon-condensed state in neutron-star matter and the MKN formed in experiments are cold, dense objects originating from the common $\bar{K} - N$ and $\bar{K} - \bar{K}$ interactions in dense matter, so that they may be closely related with each other.

We have considered properties of the MKN within the framework of a relativistic mean-field theory (RMF) coupled with the nonlinear effective chiral Lagrangian[2]. It has been shown that the lowest K^- energy, ω_{K^-}, increases as the number of embedded K^- mesons, $|S|$, becomes large and that it enters into the subthreshold resonance region of the $\Lambda(1405)$ (Λ^*), where $\omega_{K^-} \simeq m_{\Lambda^*} - m_N = 467$ MeV. This is because the contribution to the energy from the repulsive $\bar{K}-\bar{K}$ interaction becomes sizable with the increase in $|S|$ as compared with the attractive $\bar{K} - N$ interaction. In this paper, we take into account the Λ^*-pole contribution as well as range terms and study these effects on the structure of the MKN.

2. Formulation

A spherical symmetry is assumed for the MKN, and the mass number A, the number of protons Z, and the number $|S|$ of embedded K^- mesons with the lowest energy ω_{K^-} are kept fixed. We start with the effective chiral Lagrangian, which incorporates s-wave interactions between the (nonlinear) $\bar{K}$ mesons and nucleons of the scalar type simulated by the KN sigma term, Σ_{KN}, and of the vector type (Tomozawa-Weinberg term). The nonlinear K^- field Σ is given as $\Sigma = \exp[2i(K^+T_{4+i5} + K^-T_{4-i5})/f]$, where $T_{4\pm i5}(\equiv T_4 \pm iT_5)$ is the SU(3) generator and f (= 93 MeV) the meson decay constant. The K^- field is represented as $K^-(r) = f\theta(r)/\sqrt{2}$ with $\theta(r)$ being the chiral angle in the condensate approximation[2]. These $\bar{K}-N$ interactions are replaced by those generated by the σ and ω, ρ mesons-exchanges, respectively, within the RMF[2].

The thermodynamic potential Ω for the MKN is derived under a local density approximation for the nucleons[2]. The correction to the energy density, $\Delta\epsilon(r)$, from the Λ^* is introduced through the second-order perturbation with respect to the axial current of hadrons, $\hat{A}_5^\mu = f\partial^\mu K^- + \cdots + (g_{\Lambda^*}/2)(\bar{\Lambda}^*\gamma^\mu p + \text{h.c.}) + \cdots$ with g_{Λ^*} being the coupling constant for $K^-p\Lambda^*$ vertex:

$$\begin{aligned}\Delta\epsilon &= -i\int d^4z\langle x|T\widetilde{\omega}_{K^-}\hat{A}_5^0(z)\widetilde{\omega}_{K^-}\hat{A}_5^0(0)|x\rangle \times \left(-\frac{1}{2}\sin^2\theta\right) \\ &\overset{\text{real part}}{\Rightarrow} -\frac{1}{2}f^2\widetilde{\omega}_{K^-}^2\sin^2\theta\left[\rho_p^s\left\{d_p + \frac{g_{\Lambda^*}^2}{2f^2}\frac{m_{\Lambda^*}-m_N-\omega_{K^-}}{(m_{\Lambda^*}-m_N-\omega_{K^-})^2+\gamma_{\Lambda^*}^2}\right\} + d_n\rho_n^s\right], \qquad (1)\end{aligned}$$

where the smooth parts $\propto d_p\rho_p^s, d_n\rho_n^s$ are the range terms with $\rho_p^s(r)$ ($\rho_n^s(r)$) being the scalar density of the proton (neutron) and the pole contribution comes from the Λ^* with γ_{Λ^*} being the width. These terms are absorbed into the effective nucleon masses. We call these contributions to the energy the second-order effects (SOE)[1]. In Eq. (1), $\widetilde{\omega}_{K^-}(r)$ [$\equiv \omega_{K^-} - V_{\rm Coul}(r)$] is the lowest energy of the K^- shifted in the presence of the Coulomb potential. The parameters, d_p, d_n, g_{Λ^*}, and γ_{Λ^*} are determined so as to reproduce the on-shell s-wave $K-N$ scattering lengths[5]. The classical K^- field equation is given from $\delta\Omega/\delta\theta = 0$ as

$$\begin{aligned}\nabla^2\theta(r) &= \sin\theta(r)\Bigg[m_K^{*2}(r) - 2\widetilde{\omega}_{K^-}(r)X_0(r) - \widetilde{\omega}_{K^-}^2(r)\cos\theta(r) \\ &- \widetilde{\omega}_{K^-}^2(r)\cos\theta(r)\left\{\rho_p^s(r)\left(d_p + \frac{g_{\Lambda^*}^2}{2f^2}\frac{m_{\Lambda^*}-m_N-\omega_{K^-}}{(m_{\Lambda^*}-m_N-\omega_{K^-})^2+\gamma_{\Lambda^*}^2}\right) + d_n\rho_n^s(r)\right\}\Bigg], \qquad (2)\end{aligned}$$

where $m_K^{*2}(r)$ ($= m_K^2 - 2g_{\sigma K}m_K\sigma(r)$) is the square of the effective mass of the K^-, and $X_0(r)$ ($= g_{\omega K}\omega_0(r) + g_{\rho K}R_0(r)$) represents the $\bar{K}-N$ vector interaction. In these quantities, g_{iK} ($i = \sigma, \omega, \rho$) are the coupling constants, while $\sigma(r)$, $\omega_0(r)$, and $R_0(r)$ are the mean fields of the σ meson and the time components of the ω and ρ mesons, respectively. Together with Eq. (2) one obtains the coupled equations of motion (EOM) for the other mesons σ, ω, ρ, and the Poisson equation for the Coulomb potential $V_{\rm Coul}(r)$:

$$\begin{aligned}-\nabla^2\sigma(r) + m_\sigma^2\sigma(r) &= -\frac{dU}{d\sigma}(r) + g_{\sigma N}(\rho_p^s(r)+\rho_n^s(r)) + 2g_{\sigma K}m_K f^2(1-\cos\theta(r)), \qquad (3a)\\ -\nabla^2\omega_0(r) + m_\omega^2\omega_0(r) &= g_{\omega N}(\rho_p(r)+\rho_n(r)) - 2g_{\omega K}\widetilde{\omega}_{K^-}(r)f^2(1-\cos\theta(r)), \qquad (3b)\\ -\nabla^2R_0(r) + m_\rho^2R_0(r) &= g_{\rho N}(\rho_p(r)-\rho_n(r)) - 2g_{\rho K}\widetilde{\omega}_{K^-}(r)f^2(1-\cos\theta(r)), \qquad (3c)\\ \nabla^2V_{\rm Coul}(r) &= 4\pi e^2(\rho_p(r)-\rho_{K^-}(r)), \qquad (3d)\end{aligned}$$

where $\rho_i(r)$ ($i = p, n, K^-$) are the number densities and g_{iN} ($i = \sigma, \omega, \rho$) the coupling constants. The coupled equations (2) and (3a)–(3d) are solved self-consistently, and the density distributions $\rho_i(r)$ and other quantities are obtained as functions of the radial distance r.

3. Numerical Results

We take the $^{15}_{8}$O (A=15, Z=8) as a reference nucleus. The K^- optical potential depth U_K is chosen to be $U_K = -80$ MeV.

3.1. Density profiles

The density distributions of the protons, neutrons, and the distribution of the strangeness density [$=-\rho_{K^-}(r)$] are shown for $|S|$=4 and 8 in Fig. 1. The solid lines are for the previous result without the SOE[2], and the dashed-dotted lines for the present result with the SOE. Due to the

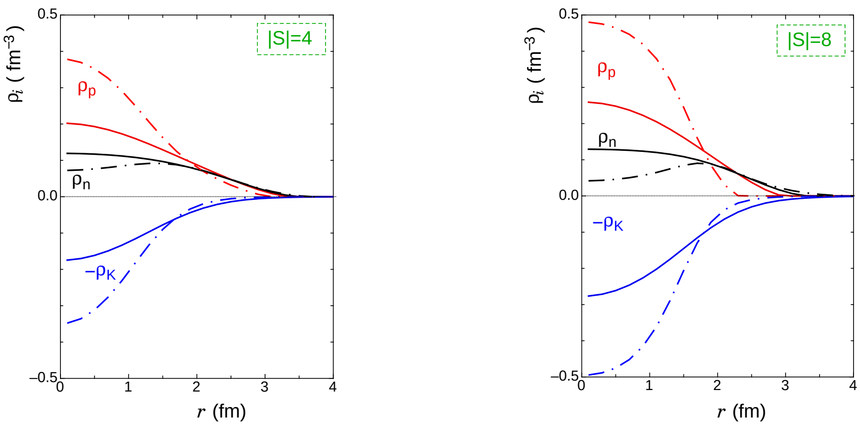

Figure 1: The density distributions of protons, neutrons, and the strangeness density [$=-\rho_{K^-}(r)$] for the MKN with A=15, Z=8, and $|S|$=4, 8 in the case of U_K=−80 MeV.

SOE, the K^- mesons and the protons are attracted more to each other than the case without the SOE, since in the former the K^- lies below the resonance region of the Λ^* and feels an additional attraction through coupling with the Λ^* pole. As a result, the central densities of the protons and K^- mesons become larger. On the other hand, neutrons are pushed outward from the center of the MKN due to the weakly repulsive effect from the range term ($\propto d_n\rho_n^s$, $d_n < 0$ in Eq. (2)). These features become remarkable for a large value of $|S|$ (Compare the cases of $|S|$=4 and 8). The central baryon density $\rho_{\rm B}^{(0)}$ ($=\rho_p(r = 0) + \rho_n(r = 0)$) becomes $\rho_{\rm B}^{(0)} \sim 3.5\,\rho_0$ with $\rho_0 = 0.153$ fm^{-3} for $|S| \sim 8$. One can see a "neutron skin" structure with a thickness (1−2) fm for $|S| \sim 8$. In addition, for a larger $|S|$, the proton and K^- density distributions tend to be more uniform near the center.

3.2. $|S|$-dependence of the lowest K^- energy and binding energy

In Fig. 2, the lowest energy of the K^-, ω_{K^-}, is shown as a function of $|S|$. The energy difference per unit of strangeness, $[E(A, Z, |S|) - E(A, Z, 0)]/|S|$ ($=m_K - B(A, Z, |S|)/|S|$ with $B(A, Z, |S|)$ being the binding energy of the MKN), is shown as a function of $|S|$ in Fig. 3. In these figures the solid lines are for the result without the SOE[2], and the dashed-dotted lines for the result with the SOE. From Fig. 2, the ω_{K^-} is shown to be lowered by ~ 40 MeV from that without the SOE due to the additional attraction brought about from the Λ^* pole. Nevertheless, ω_{K^-} increases with

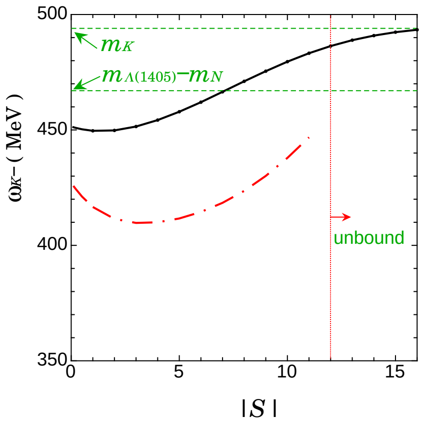

Figure 2: The lowest energy of the K^-, ω_{K^-}, for the MKN with A=15, Z=8, and $|S|$=2, 8 in the case of U_K=−80 MeV.

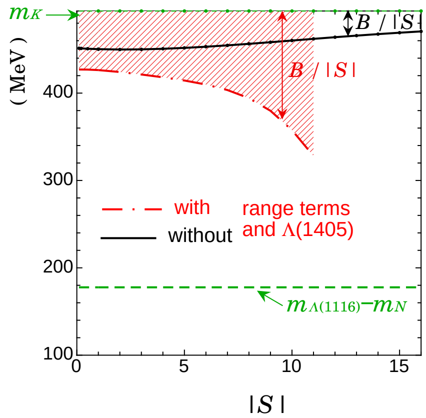

Figure 3: The energy difference per $|S|$, $[E(A,Z,|S|) - E(A,Z,0)]/|S|$ as functions of $|S|$. $B(A,Z,|S|)$ is the binding energy of the MKN.

an increase in $|S|$ since the repulsive $\bar{K} - \bar{K}$ interaction overwhelms the attractive $\bar{K} - N$ interactions at large $|S|$. For $|S| \geq 12$ (in the case of $U_K = -80$ MeV), K^- mesons become unbound, where $\omega_{K^-} \gtrsim m_{\Lambda^*} - m_N$ above the Λ^*-resonance region.

From Fig. 3, the $B/|S|$ steadily increases with $|S|$ in the case in which the SOE is included, while it shows little dependence upon $|S|$ without the SOE. One finds that $m_K - B/|S| > m_{\Lambda(1116)} - m_N$, where $m_{\Lambda(1116)}$ is the free mass of the lightest hyperon $\Lambda(1116)$. Hence the MKN decays through strong processes such as $K^- NN \to \Lambda(1116)N$, so that it is not stable as a self-bound object. This result qualitatively agrees with that in Gazda et al.[3].

4. Concluding remarks

With regard to creating self-bound objects for the MKN, hyperon-mixing effects may be responsible for formation of more strongly bound states. It has been shown in a liquid-drop picture that coexistence of antikaons and hyperons leads to highly dense self-bound objects, which may decay only through weak processes[7]. There is a controversy about the possible existence of such objects depending on the adopted models and approximations[6]. A realistic framework including antikaons and hyperons as well as nucleons beyond the local density approximation for baryons is necessary for further investigation.

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